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Improved Characterization of Transmitted Wavefront Error on CADB® Epoxy-Free Bonded Solid State Laser Materials

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ABSTRACT

Current state-of-the-art and next generation laser systems—such as those used in the NIF and LIFE experiments at LLNL—depend on ever larger optical elements. The need for wide aperture optics that are tolerant of high power has placed many demands on material growers for such diverse materials as crystalline sapphire, quartz, and laser host materials. For such materials, it is either prohibitively expensive or even physically impossible to fabricate monolithic pieces with the required size. In these cases, it is preferable to optically bond two or more elements together with a technique such as Chemically Activated Direct Bonding (CADB[©]). CADB is an epoxy-free bonding method that produces bulk-strength bonded samples with negligible optical loss and excellent environmental robustness. The authors have demonstrated CADB for a variety of different laser glasses and crystals. For this project, we will bond quartz samples together to determine the suitability of the resulting assemblies for large aperture high power laser optics. The assemblies will be evaluated in terms of their transmitted wavefront error, and other optical properties.

Keywords: Optical bonding, quartz rotators

1. INTRODUCTION

Several projects are underway worldwide which promise to demonstrate fusion ignition and gain. The first of these to be completed is the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory[1].[1,2] In 2010, the team of scientists and engineers operating the NIF will start a campaign to demonstrate fusion ignition, which could serve as the basis for a national program to develop Laser Inertial Fusion Energy (LIFE). A LIFE power generation system will have to meet all of the basic requirements of the NIF including laser requirements, target geometry, target illumination, radiation/hazardous materials handling and safety. In addition, the power generation system will have to address high average power operation of the laser system, average power effects on the target chamber, target injection and tracking, target mass production, blanket and tritium production, and the balance of plant to produce electricity.

A laser driver meeting these basic requirements was formulated based on a self consistent conceptual design for a Laser Inertial Fusion Energy (LIFE) power plant.[3-6] Although we have used only modest extensions of existing laser technology to ensure near-term feasibility, predicted performance meets or exceeds plant requirements: 2.4 MJ pulse energy produced by 576 beamlines at 15 Hz, with 12% wall-plug efficiency. High reliability and maintainability are achieved by mounting components in compact line-replaceable units that can be removed and replaced rapidly while other beamlines continue to operate, at up to ~8% above normal energy, to compensate for neighboring beamlines that have failed. Statistical modeling predicts that laser-system availability can be greater than 99% provided that components meet reasonable mean-time-between-failure specifications. In our proposed development plan, a prototype beamline is built and tested in ~4 years and a 288-beam laser system for the first LIFE demonstration power plant is built and activated in ~13 years. Timely demonstration of fusion energy is required to meet an expected growth in power plant production and displace carbon based power sources slated for this need.

One of the many optics required for this laser architecture is a large aperture (27 x 27 cm^2) 90 degree quartz rotator for the Nd:glass laser beamline. Such an optic is larger than any current quartz crystal, and many years of growth scaling will be required to eventually scale the optic up to full aperture. A potential alternative to growing very large crystals is to optically bond smaller apertures together.

The Chemically Activated Direct Bonding process (CADB®) has been developed by Precision Photonics Corp and results in epoxy-free optical paths that are 100% optically transparent with negligible scattering and absorptive losses at the interfaces. For YAG and similar materials, the process has been proven to offer bond strength performance

equivalent to that of bulk. It is thus exceptionally durable, reliable and resistant to changes in laser fluence, temperature, and humidity.[7] Due to the zero bond line thickness, complete conformance is ensured between the two bonded surfaces, making it ideal for this application. Using the CADB process, a small aperture quartz rotator samples were bonded together to test this alternative.

2. PREPARATION OF QUARTZ ROTATOR ASSEMBLIES

To fabricate the bonded assembly, we procured a set of 4 commercial, off-the-shelf small aperture quartz rotators from a separate vendor. As shown in Fig. 1(a), the substrates were 20mm x 20mm x 14mm, with the quartz extraordinary axis oriented normal to each square polished face. We decided to construct one rotator assembly from each pair of small aperture quartz pieces. To allow for a robust evaluation of the bonded interface in the final assembly, we polished the 14mm x 20mm face of each quartz slab at an angle of 15°. The alignment error on this angle as well as the adjacent face 90° angle were maintained at <1 arc minute, which ensured that the quartz e-axes would match up well at the bond line. Axis matching is essential in quartz because of the large optical and thermo-mechanical asymmetries in the material.

We used a special process to polish the quartz bonding surfaces. Our goal was a set of surfaces with low rms roughness, good surface quality, and minimal flatness error at the outer edges (edge roll-off). By reducing edge roll-off, we could increase the usable aperture of the optic and minimize the extent of the delaminated seams that form along the perimeter of the bonded interface. After we finished polishing, we proceeded to bond the individual quartz pieces. We used the CADB process to join the 2 pairs of slabs together into 2 larger rotator assemblies (see Fig. 1(b).

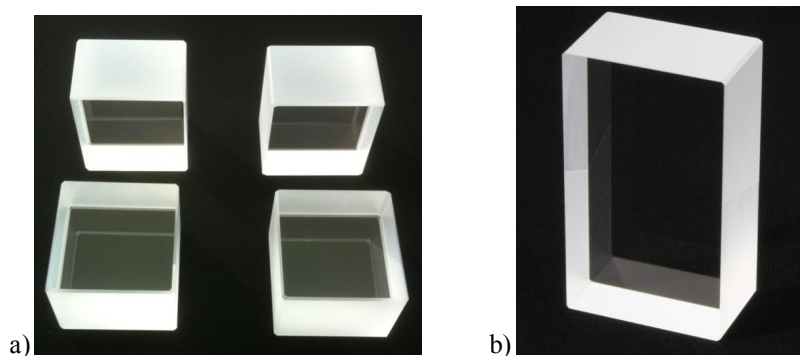a)   b)

Fig. 1: (a) Four small aperture 90 degree quartz rotators in their raw state prior to edge polishing and edge bonding. (b) One of the bonded assemblies after polishing both of the broad faces. The angled bond line is only visible along the ground side face, which was not processed after bonding.

3. BONDED QUARTZ ROTATOR EVALUATION

The substrates were prepared by creating bonding surfaces at a 15 degree angle to the front surface normal. This geometry would assure that after bonding light transmitted through the rotator at normal incidence would not travel along the bond line which would be amorphous and induce phase error. At the 15 degree angle, the bond should be invisible to the transmitted phase of the beam assuming there is no induced stress in the substrate and there are no trapped contaminants along the bond interface. The results of this initial test are shown in Fig.2 where the "hairline" edge of the original parts is still visible. These edges were later removed in the final polishing step, but are left visible in the figure to illustrate the geometry and bring attention to the bond area because after polishing there should be no visible evidence that the bond even exists. To test the viability of this assembled quartz rotator, an experiment was performed with a schematic shown in Fig.3. A camera was used to assess the transmission of the parallel polarizers with the rotator cancelled by the waveplate (near 100% transmission) and with the waveplate aligned to the polarization such that the 90 degree rotator creates a crossed polarization condition (near 0% transmission). The contrast between these two states was measured to be 1500:1 which is sufficient to determine the relative alignment of the two rotators within ~1.5 degrees. This assessment was made by translating the rotator orthogonal to the beam so that the beam could sample one half of the crystal, the bond area, and the other half successively. At each location the polarization contrast was evaluated. Initial measurements could find no difference in the transmitted intensity between the left and right halves

including the bonded area. These results indicate excellent crystallographic alignment control between the two samples, exceeding the requirements of a LIFE rotator optic. The second test evaluated the reflectivity of the bond interface using a relative measurement method accomplished two ways: between the known Fresnel reflectivity from the surface and the reflected beam from the interface, or measure the extinguished intensity through crossed polarizers relative to the reflected beam from the interface. In both cases, this reflectivity was found to be $\sim 5\times 10^{-6}$ indicating a very clean interface, very thin bond, and < 1.5 degrees alignment of the crystalline axis.
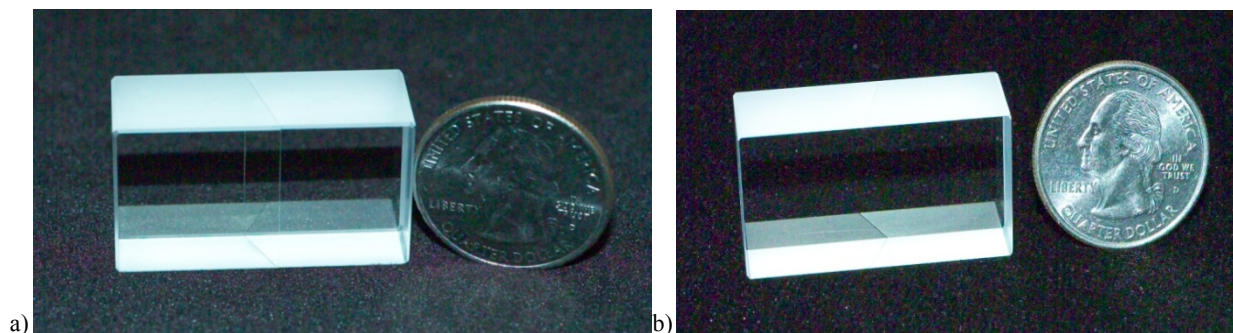

Fig. 2: a) small aperture 90 degree quartz rotators bonded together to create a single large aperture rotator. This unfinished substrate shows the residual edges of the original subcomponents which was removed by polishing in the finished part (b) to create a single contiguous aperture.
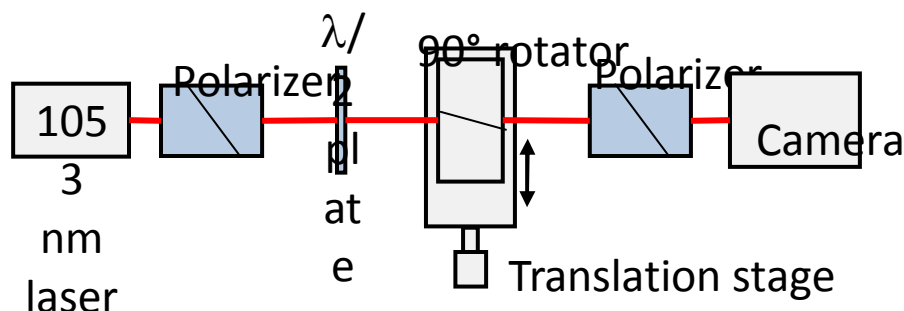

Fig. 3: Experimental setup for evaluating efficacy of bonded 90 degree quartz rotator

The final process step was to touch-up polish the input/output faces of the rotator assembly. This step was necessary to remove the fine seams of delamination at the outer edges of the bonded interface so that the bond line would be completely invisible to an incident laser. In addition, the final polishing step was needed to eliminate any path length differences through the rotator as a function of position. Such path length differences can arise whenever there is a slight (~30 arc second) misalignment of the 2 quartz pieces during bonding or if there is a small residual pyramidal error during the wedged face polishing step—see Fig.4. We discovered that the post-bond processing of the quartz assemblies was fairly difficult relative to ordinary glass, e.g., fused silica, assemblies due to the large sensitivity of the quartz assembly to thermal shock.

During our process development, we used one quartz assembly as a test piece for the more aggressive fabrication steps like coarse grinding. As a result, the outer surface of this first quartz assembly was damaged and rendered unsuitable for laser-based evaluation of the bonded interface. However, we were able to extract some useful information from the test piece by prying apart the bond. After exerting considerable force on the assembly in a direction parallel to the bond plane, we succeeded in separating the two quartz pieces in the assembly. Due to the very high bond strength, we saw that a major portion of the bonded interface did not delaminate—instead the bulk quartz material fractured above and below the original bond line (see Fig. 5). This bulk material fracture actually extended almost 400 microns above the plane of the original bond, which implies that there was negligible subsurface damage below the polished surfaces. It appears that the polished quartz material at the two mating surfaces was bonded so

strongly that the bulk crystalline quartz fractured before the bond gave way. The observed high bond strength bodes well for future work that we have planned for larger edge-bonded quartz assemblies.

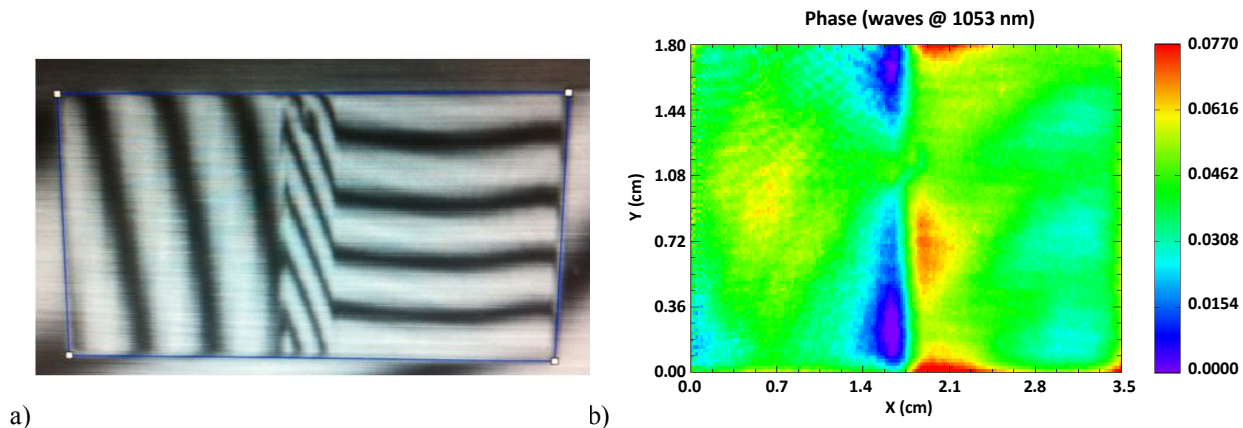a)   b)

Fig. 4: (a) Transmitted wave interferogram showing three discrete zones in the quartz assembly after initial bonding. Each zone has a different optical path length due to slight misalignment of the polished faces. (b) Transmitted wavefront error (TWE) OPD map after polishing of the input/output faces of the rotator assembly.

Fig. 5: Quartz rotator pieces after prying apart one of the bonded assemblies. Bulk material fracture zones are visible as elliptical regions near the center of each bonding surface. The shape of each zone is a mirror image of the other.

4. CONCLUSIONS

All of the above results are very promising for scaling this bonding technique to full aperture LIFE optics. The final polished part will now undergo further testing such as: transmitted wavefront and bond interface damage testing. In the interest of moving this technique forward quickly, larger substrates (each 5 x 8 cm^2) have already been procured and are being prepared for a larger aperture demonstration of this bonding technique.

ACKNOWLEDGEMENTS

REFERENCES

[1] C.A. Haynam et. al., "National Ignition Facility Laser Performance Status," *Appl. Opt.* **46**, 3276 (2007).

[2] E.I. Moses, "Ignition on the National Ignition Facility: a path towards inertial fusion energy," *Nuc. Fus.*, **49**, 104022 (2009).

[3] M. Dunne et. al., "Timely Delivery Of Laser Inertial Fusion Energy (LIFE)," *Fus. Sci. Tech.*, to be published 2011.

[4] J.F. Latkowski et. al., "Chamber Design for LIFE," *Fus. Sci. Tech.*, to be published 2011.

[5] T. Anklam et. al., "LIFE System Design," *Fus. Sci. Tech.*, to be published 2011

[6] Bayramian, et. al., "Compact, efficient laser systems required for laser inertial fusion energy," *Fus. Sci. Tech.*, to be published 2011.

[7] N. Traggis and N. Claussen, "Improved bond strength characterization of chemically activated direct bonding (CADB) epoxy-free bonded solid state laser materials", SPIE Proceedings, Vol. 7578: Solid State Lasers XIX: Technology and Devices, (2010).